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DEVELOPMENT AND FLIGHT TEST OF A HELICOPTER COMPACT, PORTABLE, PRECISION LANDING SYSTEM CONCEPT

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SUMMARY

A novel, airborne, radar-based, precision approach concept is being developed and flight tested as a part of NASA's Rotorcraft All-Weather Operations Research Program. A transponder-based beacon landing system (BLS) applying state-of-the-art X-band radar technology and digital processing techniques, has been built and is being flight tested to demonstrate the concept feasibility. The BLS airborne hardware consists of an add-on microprocessor, installed in conjunction with the aircraft weather/mapping radar, which analyzes the radar beacon receiver returns and determines range, localizer deviation, and glide-slope deviation. The ground station is an inexpensive, portable unit which can be quickly deployed at a landing site. Results from the flight test program show that the BLS concept has a significant potential for providing rotorcraft with low-cost, precision instrument approach capability in remote areas.

INTRODUCTION

A self-contained navigation system requiring minimum ground-based equipment is desirable to make full use of the helicopter's unique capability of remote-site, off-airport landings. In pursuing this goal, the NASA Ames Research Center is conducting cooperative research with the University of Nevada, Reno, and the Sierra Nevada Corporation to develop the use of airborne weather radar as a primary navigation aid for helicopter approach and landings in instrument flight rules (IFR) conditions. In the first phase of this effort, the detection of passive ground-based corner reflectors using a device called an echo processor was successfully demonstrated (Ref. 1). Use of this passive-reflector detection scheme in the overland environment provides pilots with a target on their radar display, and gives them the range and bearing information necessary for a nonprecision approach to the landing site.

To expand on the echo processor technology, a second phase of the research program was undertaken with the objective of developing and demonstrating the feasibility of a weather radar-based precision approach concept. The feasibility criteria for this concept included (1) minimal, passive, or battery-powered ground-based equipment; (2) the same pilot technique for flying the approaches as for instrument landing system (ILS) approaches; and (3) airborne weather/mapping radar modifications that could be accomplished as inexpensive retrofits for current civil radar systems.

To meet these objectives, a concept was pursued whereby an array of specially designed directional passive reflectors oriented along the localizer track would provide the directional signals necessary to derive ILS-type guidance. By using an on-board digital microprocessor installed in conjunction with the airborne weather radar, glide slope and localizer guidance would be calculated and displayed to the pilot on the existing ILS course deviation indicator (CDI). The reflector-based ground station would need no ground power, but would require 1.2 to 1.8 km (4000 to 6000 ft) of terrain for installation of the reflector array when used in conjunction with civil weather/mapping radar systems. Although this requirement would not be a problem for aircraft landing on conventional runways, it would be impractical for heliports.

An alternative to the radar reflector array, a radar transponder-based ground unit, has proven to be much more practical. An X-band transponder beacon with multiple-pulse reply capability was modified to reply through an array of directional antennas. This beacon-based ground station can be packaged in a small, inexpensive, battery-powered, portable unit.

In early testing of the BLS, the concept feasibility was demonstrated (Ref. 2). Current work is in progress with the objective of refining the BLS concept by (1) improving ground station design to eliminate multipath, (2) reducing localizer sensitivity at close ranges, and (3) preserving full-weather/mapping radar capability while on a BLS approach.

This BLS concept has significant potential for a large number of applications. It differs from other portable landing system concepts in that the airborne radar is actively used to interrogate and receive the ground station signals. Thus, distance to the landing site is inherently available on-board the aircraft. Also, the ground station power requirements are small because of the pulse-type replies of the ground station instead of the continuous wave (CW) mode of operation used in other landing systems. This paper describes the BLS concept, the concept demonstration hardware, and the flight tests in progress to verify the design principles.

CONCEPT DESCRIPTION

The BLS concept represents a combination of advanced, digital signal-processing techniques and X-band radar systems. Many of the same operating principles are used for a standard ILS, with important differences being in the carrier frequency and beam-discrimination methods. The following sections describe the operating theory and the concept demonstration hardware built to validate the feasibility of a weather radar-based precision approach concept.

Landing System Concepts

The weather radar precision approach concept operates on the principle of four overlapping, narrow radar beams oriented left, right, above, and below the desired flightpath. The sketch in Fig. 1 depicts the two glide slope beams, oriented above and below the desired flightpath. With this beam orientation, as the aircraft deviates from the desired flightpath, one signal increases in amplitude and the other decreases. When all four signals are of equal intensity, the aircraft is on course. Glide-slope deviation from the desired course is proportional to the difference in received signal strength of the up-down beams, and localizer deviation is similarly derived using the left-right beams.

A survey shows that two basic types of precision approach systems are used: Fixed-beam systems and scanning-beam systems (Ref. 3). Fixed-beam systems, including ILS and BLS, provide a single approach corridor, whereas scanning-beam systems, such as the microwave landing system (MLS), have the added flexibility of pilot-selectable approach paths (Ref. 4). A summary of ILS, MLS, and BLS characteristics is shown in Table 1. Although ILS and BLS are both fixed-beam systems, there are important differences between the two. First, the carrier frequency for the ILS beams is two orders of magnitude lower than for the X-band BLS. Since antenna size to achieve a given beam width is inversely proportional to carrier frequency, the high frequency of the BLS makes it possible to use small antennas at the ground site. Second, the techniques for discriminating between the four beams are very different. For ILS, the ground signals are transmitted on a CW basis, and they are tone-modulated for purposes of discriminating between the beams. The BLS makes use of the multiple-reply capability of X-band ground transponder beacons, incorporating a high-speed switching circuit to transmit the time-sequenced replies through the four directional antennas. The on-board microprocessor installed in conjunction with the airborne weather/mapping radar can then discriminate between the four directional guidance beams based on the time sequencing of the pulses. Unlike other landing systems, the BLS is a transponder-based system, and range to the ground station is inherently available. Other landing systems require co-located distance measuring equipment (DME) or marker beacons to provide the pilot with range fixes.

Ground-Based System

The ground station consists of a modified X-band radar transponder beacon with multiple-reply capability. Normally, the first reply is used to identify position, and additional time-sequenced replies are used for identification. In a standard beacon, all replies are transmitted through an omnidirectional antenna. Power for the beacon is either 28 V DC or 50-60 Hz, 120 V AC. With the BLS concept, the beacon is modified to the extent that a logic circuit is added into the normal beacon receiver video and modulator lines. This logic circuit is used to control both the beacon transmissions and a single-pole, five-position, solid-state microwave switch connected to the beacon transmitter. The switch allows sequential transmission of beacon reply pulses from five different antennas for each interrogation. The logic operates as follows. In the absence of an interrogating signal from an airborne weather radar, switch position 1 is selected, connecting the beacon to an omnidirectional antenna. Upon interrogation, the first reply pulse is transmitted through this omnidirectional antenna, providing a beacon-type wide-coverage reply for general landing site identification. After the first reply pulse, the logic circuit sequentially switches five beacon identification pulses, four to the four directional antennas, respectively, and one back to the omnidirectional antenna. The purpose of the last omnidirectional pulse is to provide a pulse spacing between it and the first pulse that positively identifies the station. The net result of this process is the radiation of six pulses, the first from the omnidirectional antenna, followed by four directional pulses, followed by another omnidirectional pulse.

As seen in Fig. 2, the four directional antennas used for the early concept demonstration BLS ground station were standard 30-cm (12-in.) weather radar flat-plate antennas. These antennas were chosen for test purposes because of their low cost and availability, but testing revealed multipath problems associated with such small antennas. A study of antenna size versus system performance indicated that BLS antennas 60 to 120 cm (2 to 4 ft) in height would be best. Current tests are being conducted with two parabolic antennas, 23 cm (9 in.) wide and 90 cm (36 in.) high, replacing the four directional antennas. Each parabolic antenna contains two appropriately oriented feed horns so that one antenna provides localizer beams and the other provides the glide-slope beams. These directional antennas should allow for multipath-free BLS operations at glide slopes of 4° or greater.

For current testing, a change in the design is being considered in which two sector antennas replace the single omnidirectional antennas. The sector antennas are higher gain, resulting in either reduced ground station transmission power or greater BLS range. Also, proper localizer CDI indications can be derived at deviations up to ±35° from the course centerline using amplitude comparison of the sector antenna replies. The current ground station, incorporating the two parabolic antennas and the two sector antennas, is packaged on a compact, portable pallet as shown in Fig. 3.

In early BLS testing, the ground station always operated in a transponder mode. However, in current testing, a dual-mode transmission is being used to preserve full on-board weather radar capability on approach. The transmission modes include the transponder, or synchronous, mode for operation during interrogation by the airborne radar and an asynchronous mode in which the ground station transmits pulse trains 100 times per second. In the asynchronous mode, the aircraft receives localizer and glide-slope guidance, but no range information can be derived.

Airborne System

The weather/mapping radar used for the BLS demonstration flight tests is typical of radars installed for offshore operations. The radar is an X-band (9375 MHz) color radar, with an average pulse power of 8 kW, and a pulse repetition rate of 121 pulses/sec. The radar can be operated in a primary mode, beacon mode, or a combined radar and beacon mode. For early BLS testing, the normal 46-cm (18-in.) flat-plate antenna was replaced with a very small, nonscanned, wide-beam antenna. Current BLS flight testing configuration includes a separate X-band receiver to allow simultaneous BLS and weather/mapping radar operation.

The BLS processor analyzes the beacon video signal to calculate range, localizer deviation and glide-slope deviation. Localizer and glide slope deviations are displayed to the pilot on an ILS-type CDI, and range information is available on a panel-mounted digital display. The BLS processor is designed to easily interface with the airborne weather/mapping radar as shown in the installation diagram (Fig. 4). The processor is microprocessor-based with A/D (analog/digital) and D/A converters. Two signals, the beacon-receiver video and the modulator trigger, are input to the BLS processor from the radar receiver/transmitter (R/T) unit, and an automatic gain control (AGC) voltage is returned to the R/T. In the current airborne configuration (Fig. 5), a separate X-band receiver is used for the BLS guidance signals, with the processor controlling its AGC. The weather radar modulator trigger is still input to the BLS processor for range determination when the BLS is in its synchronous (transponder) mode.

System Operation

This section describes the concept demonstration BLS equipment in operation. Figure 6 shows an oscilloscope trace of the ground station beacon return with the six BLS reply pulses spaced at 6-μsec intervals. The BLS microprocessor is programmed to search this radar return for the two omnidirectional radar pulses 30 μsec apart. When consistent omnidirectional returns are received, the first is tracked and range gates are opened at each directional pulse location to measure signal strength. The first omnidirectional pulse is also used to adjust the AGC voltage, keeping the X-band receiver in its linear range and ensuring that side lobes of the directional precision guidance antennas do not generate false courses. For each guidance signal pair, the signal amplitudes are differenced, scaled, and filtered for output to the CDI.

With the current BLS dual-mode equipment, the ground station automatically switches between the synchronous and asynchronous modes. The airborne radar, sweeping a ±30° sector at a sweep rate of 24°/sec, interrogates the BLS ground station for about 0.3 sec of each 2.5 sec. Between these periods of synchronous operation, the BLS reverts to the asynchronous mode of operation to provide continuous localizer and glide-slope course deviation information.

FLIGHT TEST PROGRAM

The early concept feasibility BLS flight testing was conducted with the BLS ground station configured with four 30-cm 12-in. flat-plate antennas. These tests measured navigational and pilot tracking performance, and obtained qualitative pilot opinions of system performance. Current BLS flight testing, using the new ground station described above, has the following objectives: (1) identify any multipath problems, (2) obtain pilot comments on "course softening" at short ranges, and (3) qualitatively measure performance of simultaneous BLS and weather/radar operation.

Aircraft

The test aircraft is an IFR-equipped Sikorsky SH-3G helicopter (Fig. 7), the military equivalent of the S-61N. The SH-3G is a twin-turbine, five-bladed, single-rotor helicopter with emergency amphibious capabilities. The aircraft has a flying boat hull and two outrigger sponsons, into which the main landing wheels can retract. The rotor diameter is 19 m (62 ft), the gross weight is 8660 kg (19,000 lb), and the maximum airspeed is 120 knots. During flight testing, two pilots, the aircraft crew chief, and one to three experimenters were aboard. Experimental equipment and data acquisition system equipment were mounted on a rack in the cargo area.

Test Locations

The SH-3G helicopter is based at the NASA Ames Research Center, Moffett Field, California. System checkout and initial evaluation flights are made at Moffett Field, and quantitative data collection flights are made at the Crows Landing NALF, Patterson, California. The NASA Ames Flight Systems Research Facility at Crows Landing, equipped with radar tracking systems, a data telemetry receiver, and ground-based data monitoring and recording equipment, is used to record quantitative data to analyze BLS performance.

Approach Procedures.

The approach procedures being tested are similar to those used for standard ILS approaches. Tactical air navigation (TACAN) bearing and distance are used to position the aircraft for BLS intercept. Following acquisition of the BLS guidance, the warning flags on the BLS CDI disappear, and the pilot intercepts and tracks inbound on the BLS course. On system checkout and demonstration flights at Moffett Field, the BLS ground station is located near the approach end of runway 32R, and approaches are made parallel to the runway 32 approach corridor. Glide slopes ranging from 4° to 9° have been demonstrated. At Crows Landing, most approaches are made with the BLS ground station located 61 m (200 ft) left of the runway 35 centerline and near the STOL runway threshold. This location allows excellent tracking system coverage throughout the approaches.

FLIGHT TEST RESULTS

Figure 8 shows a typical view of the helicopter during early testing as it approaches the battery-powered BLS ground station on an approach. Note that during this early portion of the flight test program, the omnidirectional ground station antenna was replaced with a directional antenna to match signal strengths at the airborne receiver. For current testing, the directional transmissions are attenuated 10 dB to match signal strengths from the sector antennas. Testing to date has demonstrated BLS guidance intercept at ranges out to 17 n. mi. and glide slopes ranging from 4° to 9°. For quantitative evaluation, a 6.6° glide slope was used with localizer intercept 8 to 10 km (5 to 6 mi.) out from the ground station.

Pilot Comments

Pilot comments on the BLS have been favorable and enthusiastic, confirming the operational feasibility of the BLS concept. Pilot workload and piloting techniques are like those of ILS approaches. Since localizer and glide-slope intercepts and course tracking use standard ILS techniques, pilot acceptability of the BLS approaches has been excellent, and pilot training on BLS approach procedures was minimal.

Pilot comments during early testing also identified the need to reduce close-range localizer sensitivity. A fixed-base piloted simulation was conducted to investigate pilot acceptability of several localizer "course softening" algorithms. These algorithms reduce localizer sensitivity as a function of range, which is available aboard the aircraft when the BLS is in the synchronous (transponder) mode. Results of the simulation identified a number of algorithms that reduced pilot workload at close ranges. Two of the most promising of these algorithms are being incorporated in the current flight tests for further pilot evaluation.

Pilot Tracking Performance

During three data flights on which the pilots were flying under simulated instrument meteorological conditions (IMC), 25 approaches were made. Composite pilots showing the lateral and altitude tracks are shown in Figs. 9 and 10, respectively. Figure 11 shows the one-sigma standard deviations of localizer cross-track errors achieved during this BLS testing. Also shown are the comparable envelopes for 6° glide-slope MLS approaches (Ref. 5, see Fig. 14) and airborne radar approaches (ARA) to oil rigs both with and without automatic target tracking equipment (Ref. 6). The one-sigma standard deviations from glide slope for BLS and MLS approaches are shown in Fig. 12. (Note that since ARA are nonprecision approaches, there is no glide-slope tracking data for comparison.) These envelopes show that the tracking performance achieved with the concept demonstration BLS was excellent, far exceeding that previously achieved for civil ARA and comparable to that achieved on MLS approaches.

BLS Navigation Accuracy

During early BLS testing, the BLS navigation accuracy was recorded. Although this equipment was in no sense optimized for accuracy, studies of the system errors are proving useful for further development of the BLS concept. Navigation errors identified to date include bias errors and signal multipath effects.

Bias errors, particularly in the localizer course, resulted from two sources: alignment of the directional antennas on the BLS ground station with respect to each other and alignment of the BLS ground station with respect to the desired approach course. For glide slope, use of an inclinometer for setting the ground station pallet at the desired glide slope was very repeatable, with repeatability achieved over the five data flights within ±0.1°. However, ground station glide-slope antenna alignment was 0.6° above the reference plane of the ground station pallet. Setup of the localizer course by siting along the edge of the ground station pallet was less accurate, and localizer course biases of up to ±2° occurred. For the current system, an improved localizer alignment siting method is being incorporated into the ground station.

Another problem, identified early in the test program, was with multipath, particularly in the glide-slope signals. The glide slope exhibited some waviness, which was worse at the lower glide slopes. Subsequent ground tests confirmed some nonlinearities in the approach course attributable to multipath phenomena. Reduction of the multipath errors was achieved using the current 90-cm (36-in.) high ground station antennas in place of the 30-cm (1 ft) antennas of the concept demonstation BLS.

Independent of the bias BLS error, the one-sigma navigation accuracy achieved with the concept demonstration BLS was ±0.22° in localizer and ±0.14° in glide slope. Figures 13 and 14 show composite data from the flight tests, comparing the localizer and glide-slope positions calculated by the BLS with the actual localizer and glide-slope deviations as determined using the tracking radar. These navigation accuracy data points were taken over a period of 3 weeks on four separate data flights.

CONCLUSIONS

A novel X-band precision approach concept has been successfully developed, and the concept feasibility has been demonstrated in flight testing. This concept appears to have significant potential for both civil rotorcraft operations and certain military missions in which remote-site precision landing systems are required. The portability and low power consumption of the BLS ground station also make the concept attractive for emergency and rapid deployment missions that require precision approach capability. Specific project conclusions are as follows:

1. The BLS X-band ground station is portable, compact, inexpensive, lightweight, and battery powered.

2. ILS-type guidance can be derived using a small microprocessor, easily interfaced with airborne weather/mapping radar or with a separate X-band receiver.

3. Pilot workoad and piloting technique for BLS approaches are similar to those in conventional ILS approaches.

4. Approach cross track errors using the BLS are far smaller than those achieved previously for civil ARA and comparable to those achieved on MLS approaches. Glide-slope tracking errors using the BLS are also comparable with MLS.

5. One-sigma navigation accuracy achieved with early concept demonstration BLS equipment was ±0.22° in localizer and ±0.14° in glide slope with bias errors of less than ±2.0° for localizer and ±0.1° for glide slope.

6. Simulation results showed that pilot workload at close ranges can be reduced by using an on-board algorithm for localizer "course softening."

7. Use of a 90-cm (36-in.) high parabolic antenna should allow for multipath free operation at glide slopes of 4° or greater.

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TABLE 1. COMPARISON OF LANDING SYSTEMS

System characteristics	ILS	MLS	BLS
Frequency	100 MHz (localizer 300 MHz (glide slope)	5000 MHz	9400 MHz
Antenna size	Large	1.8 to 3.6 m (6 to 12 ft)	0.6 to 1.2 m (2 to 4 ft)
Signal characteristics	CW, tone-modulated	Interrupted, CW	Transponder using sequential pulses
Guidance beams	Fixed: up, down left, right	Scanning	Fixed: up, down left, right
Derivation of guidance	Beam amplitude comparison	Time between signal peaks	Beam amplitude comparison
Range data	Requires co-located DME or marker beacons	Requires co-located DME or marker beacons	Inherently available
Airborne equipment	Widely installed	Must be added	Minimum retrofit for radar-equipped aircraft

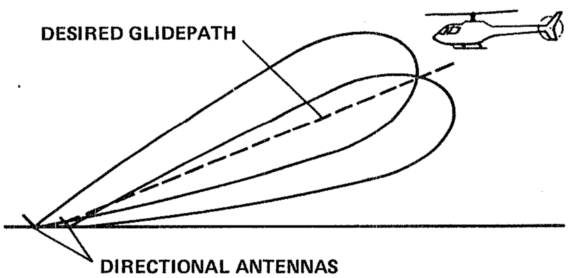

Fig. 1 Overlapping directional antenna beams provide course guidance.

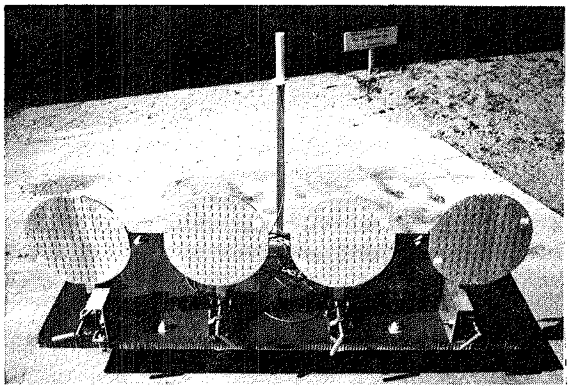

Fig. 2 Landing system ground station.

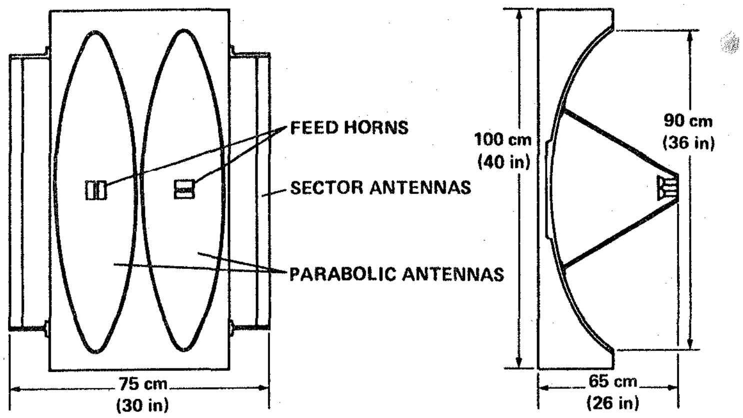

Fig. 3 Current parabolic antenna.

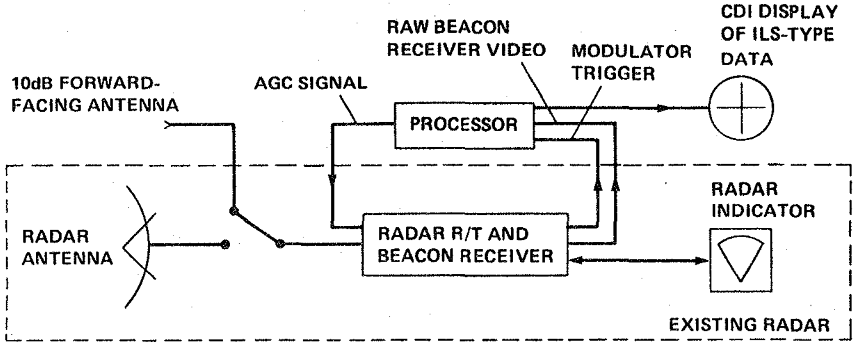

Fig. 4 Initial airborne configuration.

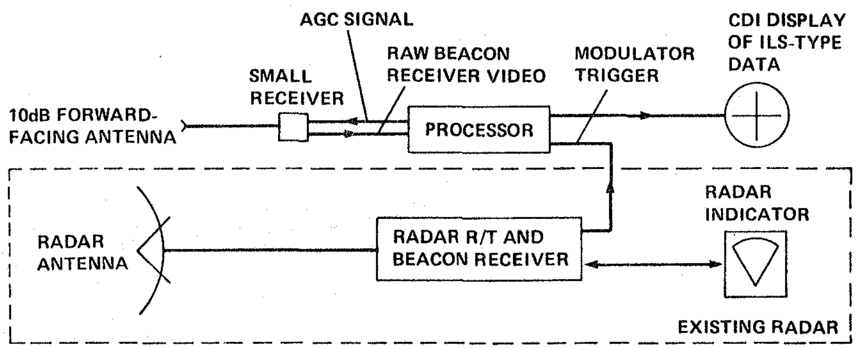

Fig. 5 Current airborne configuration.

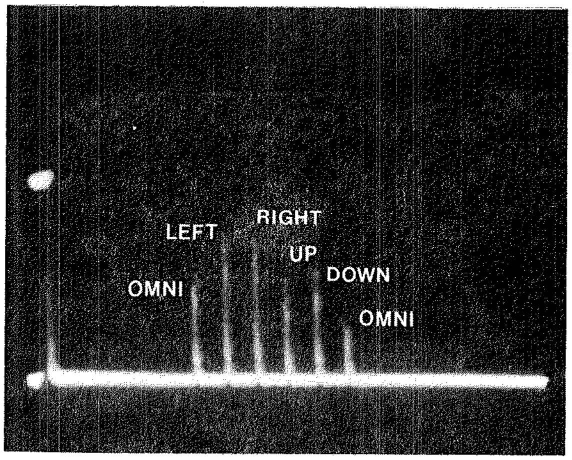

Fig. 6 Received beacon video signal aboard the test aircraft.

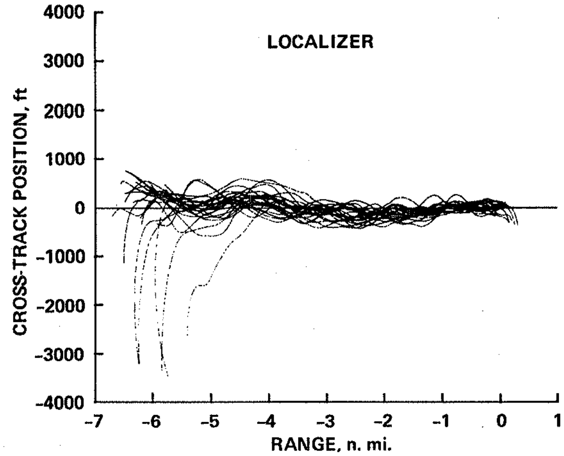

Fig. 9 Composite of x-y tracks on BLS approaches.

Fig. 7 Test aircraft.

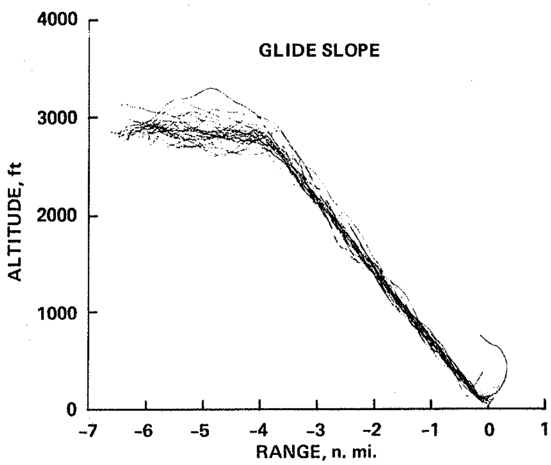

Fig. 10 Composite of altitude profiles on BLS approaches.

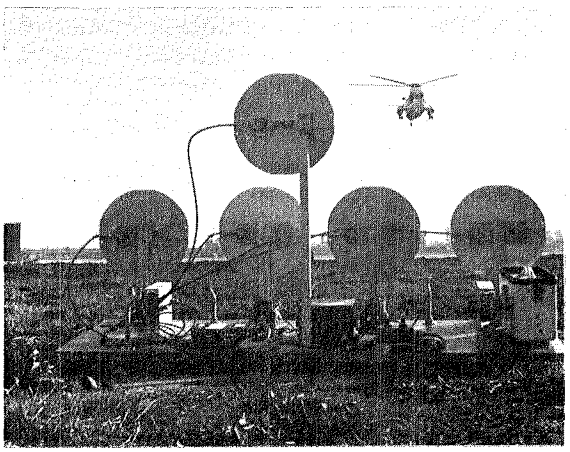

Fig. 8 BLS flight demonstration on short final approach path.

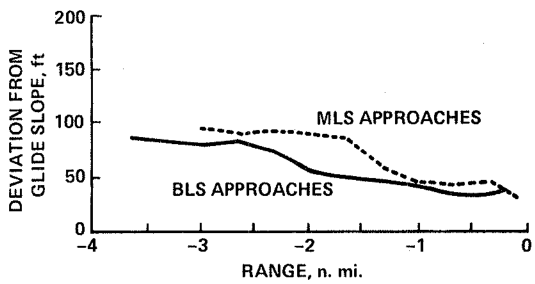

Fig. 11 Standard deviation of cross-track errors for various types of approaches.

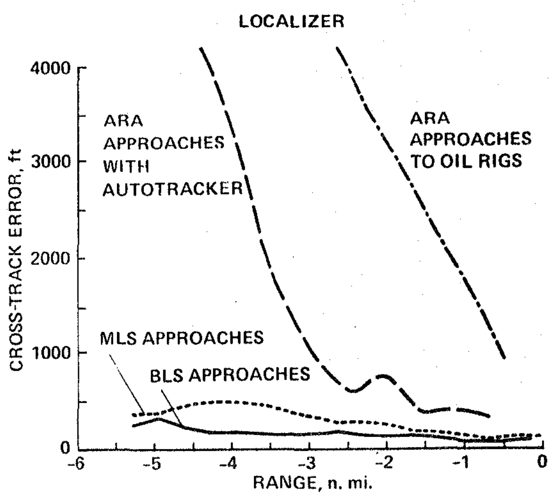

Fig. 12 Standard deviation of glide-slope errors for BLS and MLS approaches.

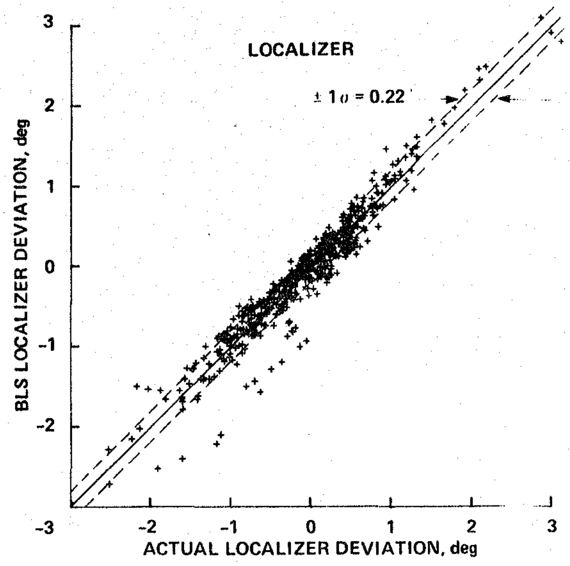

Fig. 13 Composite showing BLS localizer navigation accuracy.

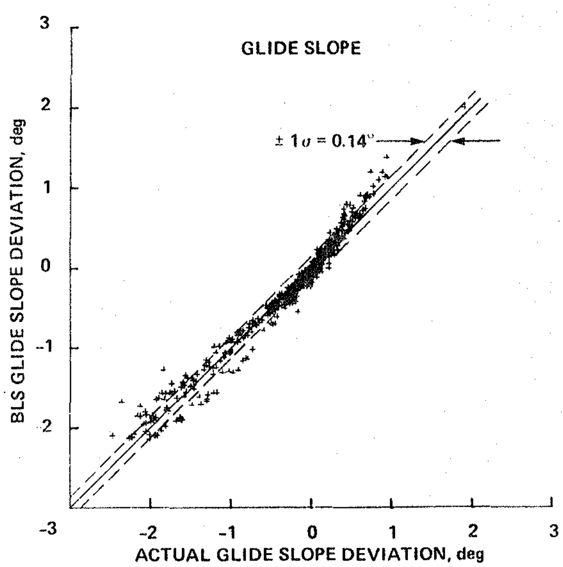

Fig. 14 Composite showing BLS glide-slope navigation accuracy.

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16. Abstract

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